REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE 2.Jun.06	3. REPORT TYPE AND DATES COVERED THESIS

4. TITLE AND SUBTITLE
EFFECT OF USING HIGH SIGNAL-TO-NOISE IMAGE INTENSIFIER TUBES ON NIGHT VISION GOGGLE (NVG) AIDED VISUAL ACUITY.

5. FUNDING NUMBERS

6. AUTHOR(S)
CAPT HIGGINBOTHAM KEITH D

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ARIZONA STATE UNIVERSITY

8. PERFORMING ORGANIZATION REPORT NUMBER
CI04-1780

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES
66

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

EFFECT OF USING HIGH SIGNAL-TO-NOISE IMAGE INTENSIFIER TUBES ON NIGHT VISION GOGGLE (NVG) AIDED VISUAL ACUITY

by

Keith D. Higginbotham

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science in Technology

20060614037

ARIZONA STATE UNIVERSITY

May 2006

ABSTRACT

A night vision goggle (NVG) image intensifier (I^2) tube's signal-to-noise ratio (SNR) determines the low-light resolution capability, therefore, the higher the SNR, the better the ability of the tube to resolve objects under low illumination conditions. Two NVG models were used to determine if visual performance would improve as a result of a goggle's higher SNR characteristic. The F4949G-TG goggles, equipped with I^2 tubes utilizing thin-filmed technology allowing for a higher SNR, and the F4949G goggles were tested. Twelve participants tested each goggle under six illumination and contrast conditions using an automated Landolt C visual acuity task. The results indicated statistically significant, although small, visual acuity differences between the two NVG models. Visual acuity scores obtained with the F4949G-TG model were better than those obtained with the F4949G at all illumination and contrast conditions examined, indicating an increase in the signal-to-noise ratio did contribute to the differences in visual performance.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Introduction

Night vision goggles (NVGs) have evolved over the decades and continue to provide enormous benefits to warfighters' advantage in a nighttime environment. The intensified image observed while viewing NVGs, however, has certain limitations as compared to daytime operations. These limitations, combined with operational limiting factors, can diminish NVG aided visual acuity during nighttime operations, especially when in low illumination and low contrast environments. Technological advances in image intensifier tube design have led to the F4949G-TG Pinnacle™ goggle featuring an auto-gated power supply and thin-filmed technology. The Pinnacle's™ thin-filmed technology gave the image intensifier tube an increase in the signal-to-noise ratio characteristic. A tube's signal-to-noise ratio determines the low-light resolution of the image tube, therefore, the higher the ratio, the better the ability of the tube to resolve objects with good contrast under low light conditions.

Several researchers have used visual acuity as a measure of NVG visual performance. Visual acuity with NVGs can be affected by many factors such as terrain illumination and contrast effects, flashblindness protection, laser eye protection, incompatible cockpit lighting, as well as the signal-to-noise ratio characteristic. Since 1991, there have been no studies identified comparing currently fielded systems with respect to the signal-to-noise ratio on NVG-aided visual acuity even though there exists specifications as to the signal-to-noise ratio required for image intensifiers.

The purpose of this research was to determine if there are any significant visual performance differences in NVG-aided visual acuity when using the new F4949G-TG goggles, equipped with image intensifier tubes utilizing thin-filmed technology, as compared to F4949G goggles with conventional technology, while completing a time-constrained visual acuity task. The F4949G-TG goggle image intensifier tubes have a higher signal-to-noise ratio, higher photosensitivity, and increased gain and resolution. The hypothesis is that an increase in the signal-to-noise ratio will contribute to an improvement in visual performance (e.g. visual acuity scores) while using the F4949G-TG NVG compared to the F4949G NVG.

Review of Literature

Aircrew members operate in complex environments where teams interact in a highly automated world. Research by the National Aeronautics and Space Administration into aviation accidents has found that 70 percent involve human error (Helmreich, 2000). A Federal Aviation Administration Civil Aeromedical Institute report found that more than two thirds of problems in any phase of flight were related to human error (Koenig, 1997). Human error can be caused by a number of physiological and psychological human factors such as fatigue, task saturation, poor communication, fixation, distraction, flawed decision making, and perception problems.

Visual perception and visual performance, for example, are dramatically diminished during operations conducted in the clandestine environment of darkness (Miller & Tredici, 1992). An obvious difference between day and night operations is the decreased illuminance. It has been well established that visual performance declines with decreasing levels of background illumination (Sturr & Taub, 1990). Loss of visual performance depends on the size and contrast of the elements of the task, whether viewing time is limited, and whether fatigue becomes a factor (Richards, 1977). Under twilight and nighttime conditions many visual abilities such as spatial resolution, contrast discrimination, stereoscopic depth perception, accommodation response, and reaction time are degraded (Plainis, Chauhan, Murray & Charman, 1999).

Night Vision Goggles

One way to improve or at least slow the visual degradation is to improve the nighttime image for the aviator or war fighter. Night Vision Goggles provide the user with an intensified image of the night environment. In general, all NVGs have three basic components: an objective lens, an image intensifier tube, and an eye lens. These three components can be designed and configured in numerous ways that can vary the trade-off between design parameters; however, the key component is the image intensifier tube.

In early warfare, battles were generally executed during daytime conditions. Occasionally missions requiring surprise attacks and stealth were conducted under the cover of darkness, however, because of major constraints, new efforts to expand nighttime effectiveness were made a priority. One of the first techniques used to enhance night vision beginning in WWI was the searchlight (McLean, Rash, McEntire, Braithwaite, & Mora, 1998). Searchlights were often bulky, required huge amounts of power to operate, and very easily detected by enemy forces. Easy detection is inherent of any night vision device of an active nature so what was needed was a passive technique that allowed night vision using only available light in the environment. The device that met this requirement was the image intensifier (I^2) (McLean, et.al., 1998).

Image intensifier tubes are completely passive in operation and are based on the amplification of light (electrons). Image intensifier tubes amplify reflected or emitted light so the human eye can distinguish objects and movements more easily in low light situations. There must be, however, a minimal amount of light present for I^2 tubes to operate since they cannot see in total darkness. The principle of image intensification is when the dimly lit scene viewed is focused on a photosensitive material, known as the photocathode, through the objective lens. The photocathode surface emits electrons proportional to the amount of light striking it. The electrons are accelerated from the photocathode toward a phosphor screen by an electric field produced through a microchannel plate (MCP), where the electrons multiply each time they strike the wall within the microscopic channel of the MCP. A visible light is produced as the electrons strike the phosphor screen. The observer views the intensified image found on the phosphor screen through an eyepiece. Figure 1 illustrates the image intensification process.

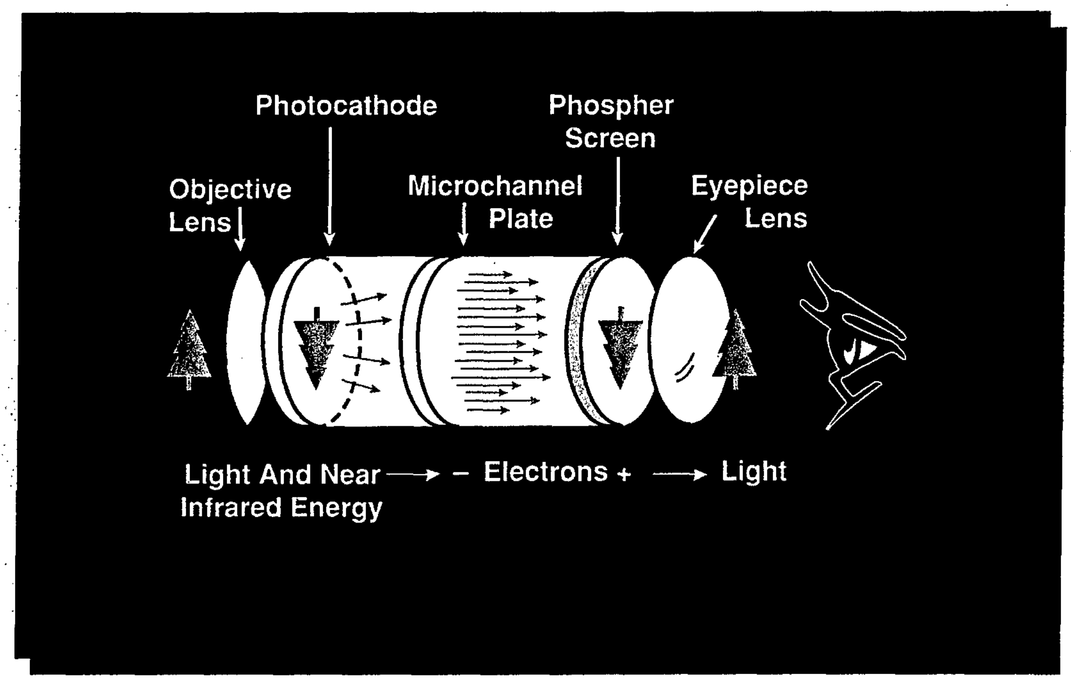

Figure 1. Diagram of the basic principle of image intensification (Antonio, Berkley, Fielder, & Joralmon, 2004).

First generation I^2 devices were introduced into military ground use in the 1960s during the Vietnam campaign used by infantry for night observation and reconnaissance missions. Second generation I^2 tubes were smaller, allowing for mounting of two tubes providing binocular viewing and transitioned into what has become known as the Army or Navy Portable Visual System (AN/PVS-5) series. In 1973, the Department of the Army adopted night vision devices for use in aviation. Several models of the basic

AN/PVS-5 NVG have been fielded: the basic AN/PVS-5 and three modified versions, the AN/PVS-5A, B, and C models. The AN/PVS-5C was not authorized for use in aviation. It was not until 1983 that third generation (Gen III) I^2 tubes were introduced to the aviation world. This initial Gen III night vision I^2 system is the AN/AVS-6 Aviator's Night Vision Imaging System (ANVIS) (McLean, et.al., 1998).

ANVIS are binocular, Gen III, I^2 night imaging systems that operate over a spectral range of approximately 625 – 950 nanometers (nm) as seen in Figure 2. This range is a result of inherent spectral sensitivity of the photocathode and a dielectric coating (minus blue filter) incorporated in the objective lens. This coating drastically attenuates energy below 625 nm and is designed to provide compatibility with blue-green cockpit lighting (McLean, et.al., 1998).

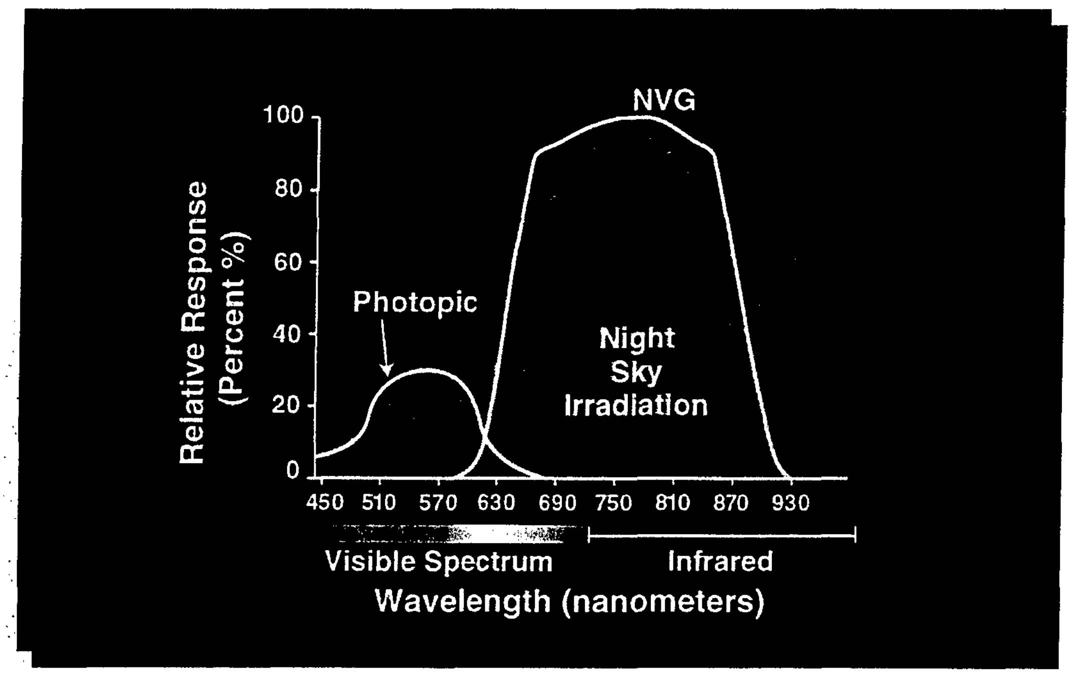

Figure 2. Spectral distribution intensifier response of NVGs (Antonio, et.al., 2004).

NVGs do provide enormous benefits by enabling personnel to carry out operations under nighttime conditions. As both civilian and military operations often occur in the stealthy environment of darkness, NVGs have become a necessity to improve situational awareness at night. The use of NVGs contributes to the enhancement of military and civilian aviation operations, ground operations, and maritime operations at night by increasing mobility, safety and mission effectiveness. Although NVGs are used to increase safety, operational effectiveness, and situational awareness at night, there are certain limitations associated with its use. The visual input does not approach that experienced using unaided vision during daylight conditions. The image is viewed on a phosphor screen that creates a monochrome image. As the image is viewed through the user's eyepieces, the user's field of view (FOV) decreases to 40 degrees field of view as seen in Figure 3. Field of view for the human eye binocular vision measures approximately 120 degrees vertically and 200 degrees horizontally.

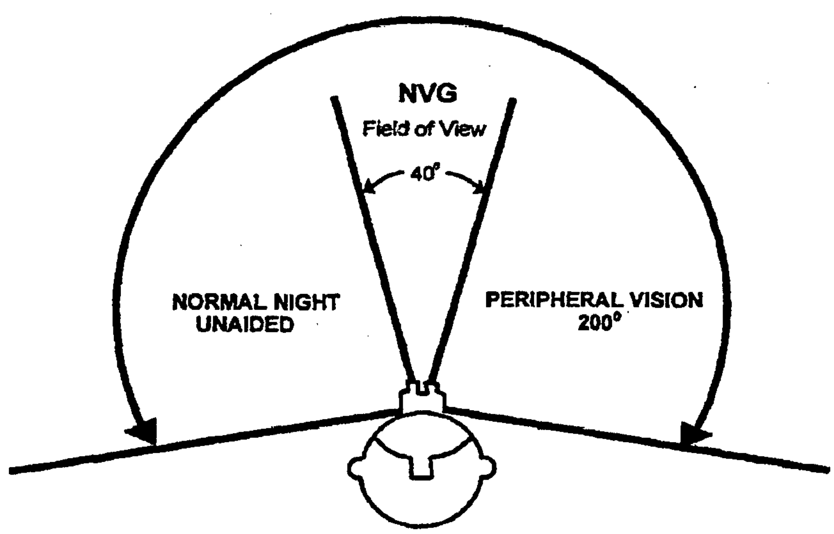

Figure 3. FOV for unaided vision and NVG-aided vision.

Many types of weather or terrestrial debris such as rain, clouds, mist, dust, smoke, and fog will affect visual performance, such as visual acuity, and can significantly increase the likelihood for visual illusions. Almost since their introduction into aviation, NVGs have produced a number of visual phenomena, which at the least have annoyed aviators and, at the worst, have been responsible for visual effects or illusions contributing to accidents.

The US military has faced recent increases in incidents and accidents in which night vision equipment has played a role. The US Army's Black Hawk helicopter fleet has suffered more than 20 fatal accidents in its 29-year service history. Approximately half of these occurred while pilots were wearing night vision devices (Johnson, 2004b). The number of aviation fatalities from mishaps across all US Department of Defense personnel rose from 65 in 2001 to 82 in 2002. US Army flight operations saw a 75 percent rise in class A accidents in 2003 compared to 2002 (Johnson, 2004a). Recent advances in night vision device technology however, may provide a path towards safer nighttime operations.

F4949G NVG and F4949G-TG NVG Comparison

The F4949G model and F4949G-TG (also known as Pinnacle™) model of NVGs are both third generation goggles but the differences lie in the design of the intensifier tubes. Two major differences in the intensifier tubes are the auto-gated power supply and the thin-filmed technology designed for the Pinnacle™ model of NVGs (ITT Industries, Night Vision, 2005a).

The auto-gated power supply is designed to allow a gating period for voltage to pass through the MCP during highly lit situations. The tube voltage is rapidly pulsed on and off to prevent saturation of the MCP. The power supply automatically varies the duty cycle depending upon how much current is passing through the MCP. At low light levels, the duty cycle approaches 100 percent, while at higher light levels it is shortened, almost shutting down for a few microseconds to allow the flux of electrons to exit the MCP before applying power once again. As a result, the goggle gain and photoresponse is not driven down by incompatible lighting in highly lit environments, thus reducing the negative effects that incompatible lighting has on the NVG-aided image. The alternative, offered with the F4949G tube standard DC power supply, allows full voltage to pass through the tube in low light situations and no voltage in the highly lit environments, allowing incompatible lighting to severely degrade the NVG-aided image as the goggle gain and photoresponse is driven down.

The addition of a film coating over the input side of the MCP had been the technological difference between the second and third generation goggles because it was found to reduce the number of damaging ions being generated during goggle use. The photocathode, without a film coating, was not resistant to ion damage so the film coating was essentially used to increase the tube life. Tests later revealed that thinning the film coating could increase the performance of NVGs. ITT Industries Night Vision Division found that significantly thinning the protective film would protect the gallium arsenide photocathode structure while still improving NVG performance. The protective film coating in ITT's new tubes is roughly 10,000 times thinner than a human hair (ITT

Industries, Night Vision, 2005a). The new Pinnacle™ tubes exceeded the same reliability standards for gain and signal-to-noise ratio, while reducing the halo effect by reducing the spacing between the photocathode and MCP, as compared to the F4949G model intensifier tubes. According to ITT Industries, Night Vision (2005a), the Pinnacle™ tube performed better then existing third generation tubes; citing the photoresponse was 22 percent higher, the signal-to-noise ratio improved 24 percent, and the halo diameter was reduced from 1.25mm to 0.70mm.

There are several technical NVG parameters worth mentioning that affect the quality of the NVG image, which are illustrated in Table 1 (ITT Industries, Night Vision, 2005b) as minimum specifications. The first notable difference is photosensitivity. The photosensitivity is 1,800 uA/lm and 2,000 uA/lm respectively for the F4949G and F4949G-TG models. Photosensitivity is the ability of the photocathode material to produce an electrical response when subjected to light energy (Turpin, 2001). The higher the value on the tube gives the user a better ability to see under darker conditions. The second notable difference is the brightness gain. The brightness gain is the ratio of the brightness of the output in units of foot-Lambert, compared to the illumination of the input in foot-candles. A typical value for a GEN III tube is 25,000 to 30,000 fL/fc. A tube gain of 30,000 fL/fc provides an approximate system gain of 3,000. This means that the intensified NVG image is 3,000 times brighter to the aided eye than to the unaided eye (Turpin, 2001). The brightness gain for the F4949G model is 40,000 fL/fc, while the brightness gain for the F4949G-TG model is 50,000 fL/fc.

The third notable difference is resolution, which means how clear and sharp an image the viewer will actually experience. The higher the values, line pairs per millimeter (lp/mm), the better the ability to provide a clear and sharp picture to the user. The resolution provided by both the F4949G and F4949G-TG tubes is typically 64 lp/mm (Turpin, 2001). The fourth notable difference is the halo size viewed through the NVGs with incompatible lighting present. Not only does incompatible lighting cause NVG gain and photoresponse to be driven down, it also will produce a blooming and halo effect surrounding the incompatible light source. The auto-gated power supply and decreased spacing between the photocathode and MCP of the Pinnacle™ goggles helps reduce the size of the halo effects. The F4949G NVG model has a halo size of 1.25 mm in diameter, just barely passing minimum operation performance standards (MOPS). Turpin, 2001, cites MOPS requires halo size be no greater than 1.25 mm in diameter. The F4949G-TG NVG model has a halo size of 0.70 mm in diameter, sufficiently passing the MOPS requirements.

Scintillation is a faint, random sparking effect throughout the image area. Scintillation is a normal characteristic of microchannel plate image intensifiers and more pronounced under low light level conditions. Scintillation is sometimes called video noise. The video noise can be controlled and measured by an indicator called Signal-to-Noise-Ratio (SNR) (Turpin, 2001). The final notable difference, and of particular importance to this study, was the signal-to-noise ratio.

According to Turpin Technologies, SNR is a measure of the light signal reaching the eye divided by the perceived noise as seen by the eye. Marinica Mirzu (2000) determined that the real performance of I^2 systems is influenced by the I^2 noise, generated by the amplification process and the optical system's capability to transfer the modulation. SNR is calculated by accounting for several factors, using the formula SNR = $(SNR_{fl} / F_A^{1/2})$ x MTF, where SNR_{fl} is the signal-to-noise ratio determined by the fluctuation in the number of photons detected by the photocathode, F_A is the amplification noise factor of the I^2 system, and MTF is the modulation transfer function of the entire system to include atmosphere, objective lens, image intensifier, and eyepiece lens. The SNR_{fl} is determined by a wide variety of factors. Target contrast, reflectivity, shape, and luminance are just some of the factors. Spatial frequency transmitted, photocathode luminance sensitivity, atmosphere and optics transmittance, integration time of the human eye, objective lens setting, and electron changes sum up the multitude of factors affecting SNR_{fl} and the final SNR (Mirzu, 2000). Turpin (2001) contends that the signal-to-noise ratio is arguably the single most significant factor in determining a system's ability to see when it gets dark.

The SNR specifications for the F4949G and F49494G-TG tubes respectively are a minimum of 21:1 and 26:1. SNR takes into account the photosensitivity as the electron image is reconverted to visible light and the "noise" contribution of the microchannel plate. A tube's SNR determines the low-light resolution of the image tube, therefore, the higher the SNR, the better the ability of the tube to resolve objects with good contrast under low light conditions thus reducing that amount of video noise or scintillation from the user's view. The result is an increased ability to see under increasingly darker conditions. Although the F4949G-TG tubes vary from the F4949G tubes with respect to signal-to-noise ratios, as well as other specifications that impact the overall quality of the NVG image, there has been no study accomplished in which visual performance is measured and compared between the two models. Visual acuity has been widely used as a metric to measure visual performance while assessing differences between NVG technologies.

Table 1

F4949G and F4949G-TG Tube Minimum Specifications

GOGGLE MODEL	F4949G	F4949G-TG
MANUFACTURER	ITT	ITT
PHOTOSENSITIVITY (uA/lm)	1800	2000
SPECTRAL RESPONSE	Class B	Class B
RESOLUTION (lp/mm)	64	64
SIGNAL-TO-NOISE RATIO	21:1	26:1
LUMINANCE GAIN @ 2 X 10^{-6} fc (fL/fc)	40000	50000
HALO MAX (mm)	1.25	0.70

Visual Acuity

Visual acuity is a measure of the ability of the human eye to resolve spatial detail. Snellen visual acuity commonly is used and is expressed as a comparison of the distance at which a given set of letters are read correctly to the distance at which the letters would be read by someone with clinically normal eyesight. A value of 20/80 indicates that an individual reads at 20 feet the letters normally read at 80 feet. Normal visual acuity is expressed as 20/20 and represents 1-arcminute separation between the dark or light periodic components of the resolution target whether the targets are letters or bars (McLean, et.al., 1998).

All visual acuity scores indicate the angular size of detail that can just be resolved; in other words, they express a minimum angle of resolution. As a result, visual acuity can also be designated in terms of the logarithm of the minimum angle of resolution (logMAR). Two concepts need to be understood. One is that 1 log unit represents a factor of 10 times and the other concept is that saying a quantity changes by a certain number of log units is equivalent to saying that it changes by a particular ratio. An acuity of 20/200 represents a minimum angle of resolution of 10 arcminutes. Since the logarithm of 10 is 1.0, a 20/200 Snellen acuity can be expressed as a logMAR of 1.0. Using the same concept, a 20/20 Snellen acuity is a minimum angle of resolution of 1 arcminute, and since the logarithm of 1 is 0.0, 20/20 is equivalent to a logMAR of 0.0 (Bailey, 1980). The major advantage of using logMAR to specify visual acuity is because it is more of a standard visual acuity designation regardless of testing distances. Another advantage is it allows partial success in reading near threshold size. For example, on a chart with five letters per row and 0.1 log unit step size, each letter would be worth a 0.02 log unit value. If a subject were to read the 0.70 row correctly and only one letter on the 0.60 row, the subject would receive credit for 0.02 for that row, resulting in a score of 0.68 logMAR.

Calculating the average visual acuity results and standard deviation is not difficult but has been done incorrectly. For the correct average visual acuity, the geometric mean must be used. Modern visual acuity charts follow a geometric progression such as a logarithmic scale. Holladay (1997) explains that the logMAR value of zero corresponds with the Snellen acuity of 20/20 and the logMAR value of 1.00 corresponds with the Snellen acuity of 20/200 (ten times or 1 log unit worse than 20/20). Intuitively, the halfway point is logMAR value of 0.5, or 20/63. This is the correct average because geometrically it is halfway between 20/200 and 20/20. The two incorrect methods would be to take the arithmetic average of the Snellen denominators or the arithmetic average of the decimal acuity. The simplest method for computing the proper average visual acuity is to convert any notation into the logMAR equivalent and then take the average of the logMAR values.

Boff and Lincoln (1988) cite three common methods of visual acuity assessment; Snellen Letter Charts, Square-Wave Grating Charts, and Landolt C Charts. However, deficiencies with different methods used for visual acuity measurement need to be addressed. Bailey and Lovie (1976) found many charts have stimuli that do not present an equivalent task and the spacing between letters and rows rarely have any systematic or logical relationship to letter size. Optometrists assess patients' visual acuity frequently by using the Snellen eye chart. The chart displays rows of letters starting with a very large size (20/200) and stepping down to the smallest (20/10), however the lines on this chart do not always follow a logarithmic letter size progression (Pinkus and Task, 1998). The square-wave grating pattern have been cited by Pinkus and Task (1998) as a means for pilots to do a quick verification that their NVGs were operating correctly and were capable of resolving detail to a specified level. One limitation of the grating pattern is that only two orientations are possible and can be easily memorized. Another assessment method uses Landolt C stimuli. Bailey and Lovie (1976) state that letters used in a chart should be of equal legibility and follow a geometric progression such as uniform steps on a logarithmic scale. This principle has been generally accepted and is optimally achieved in charts that use the Landolt C stimuli. The Landolt C is a perfectly circular C (no serifs) that has a specified contrast and gap size. The gap size is varied, as is the orientation. The observer's task is to detect the orientation of the gap. This method may be a less complex information-processing task than identifying various letters (Sheedy, Bailey, & Raasch, 1984).

According to Raasch, Bailey, and Bullimore (1998), the 1980 Committee on Vision, Working Group 39 of the National Research Council (NRC) issued a report that addressed several aspects of visual acuity measurement. The working group identified four issues that Raash, et.al. addressed in their study: (1) comparison of optotypes to the Landolt C; (2) the graduation and range of optotype size; (3) the number of symbols of each size level; and (4) the method of scoring. The Landolt C has been proposed as the standard optotype, a logarithmic size progression of 0.1 log units should be used as most authors agree that a logarithmic size progression offers the greatest practical advantages, and that all 10 letters in the series be presented at each size level. Landolt Cs can be presented on a computer monitor in one of eight orientations and in an automated and controlled visual acuity measurement using a computer software program called the "Freiburg Visual Acuity and Contrast Test".

Freiburg Visual Acuity and Contrast Test

The Freiburg Visual Acuity and Contrast Test (FrACT) has been employed in two recent USAF studies. The FrACT is a good alternative to NVG chart presentation methods because it uses a Landolt C stimuli presentation, it controls duration of stimulus, allows for 8 orientations (giving an eight-alternative forced-choice test), and it calculates an average visual acuity score recorded for all the presentations after a complete trial. With proper NVG filtering and monitor adjustment, light levels can be controlled and the monitor contrast can remain stable.

Angel and Baldwin (2003) conducted the only known visual acuity experiment using NVGs and the Freiburg Visual Acuity Test presentation, studying the changes in visual acuity with different NVG eyepiece diopter settings. The visual acuity task was presented on a monitor and was made NVG compatible by filtering with a Nightshield Full Color LCD Class B filter and an additional neutral density filter. The display was viewed through a circular aperture centered on a white foam board at 20 feet viewing distance. The background foam board was illuminated at 0.25 moon disk illumination (1.58×10^{-9} watts/cm^2) provided by a custom-made halogen light source. The contrast of the Landolt C as seen with the NVG was measured at 50 percent.

After 24 presentations the computer-calculated visual acuity was recorded and the subject initiated the next trial. With room lights off, subjects dark-adapted, and NVG filters in place, the subject focused the NVG objective and eyepiece lenses to optimize NVG visual acuity for viewing the letter C on the computer display. Each subject recorded one NVG visual acuity run (3 trials/run) with each of the user-selected eyepiece diopter settings and three NVG visual acuity run for each fixed setting for a total of twelve runs (36 total trials/subject). All visual acuities, with and without NVG, were obtained in one session that lasted about an hour. Angel et.al. achieved conclusive and consistent results assessing NVG-aided visual acuity using the Landolt C computer presentation allowed by the Freiburg Visual Acuity Test software. The only other study found to have used a computer presentation, however not the Freiburg Visual Acuity Test software, was the Levine and Rash (1989) study of the effects of NVG flashblindness protection on NVG-aided visual acuity. This study, and other studies that used NVG resolution charts for visual acuity assessment, are presented in greater detail as we outline NVG operational performance limitations and the effects on NVG-aided visual acuity.

NVG Operational Performance Limitations and Visual Acuity

A number of studies have been conducted to investigate operational factors that can degrade visual acuity with I^2 systems. Operational factors that may affect NVG visual acuity are terrain illumination and contrast effects, flashblindness protection, laser eye protection, and incompatible cockpit lighting, just to name a few.

While visual acuity can define the limiting spatial resolution available through the various I^2 devices, it primarily gives information relating to the limit for detecting a separation between two high contrasting objects, not taking into account for objects of different contrasts. Therefore is it more meaningful and more important to obtain a measure of visual acuity at various levels of contrast. Illumination and contrast effects on NVG-aided visual acuity are well established. A study conducted by Kotulak and Rash (1992) investigated effects of night sky condition, target contrast, and generation of I^2 device on visual acuity. It was found that the difference in visual acuity between the 2nd and 3rd generation I^2 devices widens under two conditions: 1) when target contrast is constant, but night sky irradiance decreases, and 2) when night sky radiance is constant, but target contrast decreases. Furthermore, it was found that for a given I^2 generation, visual acuity falls off more rapidly for a low contrast target than for a high contrast target as night sky radiance decreases. As targets reflect less and less contrast and as the night sky irradiance decreases, a sparkling effect in the image, called video noise, can be more pronounced. An image intensifier tube yielding a higher SNR could allow for improved visual performance under those darker conditions.

Riegler, Whiteley, Task, and Schueren (1991) published a study showing the effect of SNR level on visual acuity for different luminance levels and contrasts using NVGs. Riegler et.al. used a zoom lane comprising of an electronic cart for subjects to sit in during the visual acuity trials. The subject seated in the cart traveled along a 12.2-meter track and was moved as close to the Landolt C target stimuli as needed to determine the orientation of each C on the chart. A moonlight simulator was used to approximate the luminance intensity levels of different illumination conditions and a photometer was used to measure the photometric luminance of the charts and background several times during each session. Four PVS-7 image intensifier tubes were used that ranged in value from a SNR of 11.37 to 17.92. Visual acuity was assessed for two levels of contrast as well, 20 and 95 percent. As might be expected the largest visual acuity differences were due to changes in contrast of the targets and light level. The increase in visual acuity from a tube with a SNR of 11.37 to 17.92 depended on the contrast and lighting conditions. For the low contrast (20 percent) and low luminance (0.01 moon disk) condition, the improvement in visual acuity was about 22 percent for the higher SNR tube. At the high contrast (95 percent) and high luminance (0.25 moon disk) condition, the improvement was only about 10 percent. Riegler et.al. concluded that an increase in SNR has the greatest impact on visual performance under conditions of lower illumination but negligible improvements under different contrast levels.

The modem battlefield with its high tech weaponry is forcing the aviator to don additional protective devices. One such device that has been considered is flashblindness protection. Use of these add-on devices will compromise visual performance with NVG-aided visual acuity if they attenuate the device's output luminance. Levine and Rash (1989) investigated the effects of flashblindness protection on visual acuity. The study looked at visual acuity across three ambient light levels (twilight, moonlight, and starlight) and three contrast levels (low, medium, and high). Subjects were seated in a darkened room 20 feet from a 12-inch monochrome CRT monitor. Subjects viewed the CRT display through a single pair of AN/PVS-5A NVGs mounted on a table. Both height and interpupillary distance of the NVGs were adjusted for each individual subject. Neutral density filters were used to simulate protective lenses used to prevent flashblindness. Background luminances were measured with a photometer and adjusted to simulate the appropriate luminance levels associated with twilight, full moon, or starlight. Three contrast conditions – 90, 30, and 3 percent – were used to represent high, moderate, and low contrast. Subjects were permitted 10 minutes to adapt to the dark environment and then instructed to focus the NVGs. A Snellen optotype E was displayed on the monitor and the subject indicated the orientation of the E with an appropriate movement of a hand-held joystick. Acuity thresholds were determined by incorporating a four-alternative forced-choice test.

The test began as a suprathreshold E was presented randomly in one of four orientations. The targets would get smaller as the subject responded correctly, however, when the subject responded incorrectly, larger-sized targets were presented until the subject responded correctly once again. Levine and Rash, found that the effect of reducing output luminance to the eye varied as a function of both ambient light level and target/background contrast. Mean acuities ranged from 20/50 under the most favorable viewing condition (twilight and high contrast) to greater than 20/400 under the poorest viewing condition. Inspection of the data revealed no significant differences in acuity between the "filter" and "no filter" conditions under any combination of illumination and contrast, even though looking through the "filter" reduced the luminous transmission of the goggles by nearly 80 percent.

Small, hand-held laser designators are widely used as target designators and range finding. Despite their compact size, laser pointers are often powerful and potentially harmful lasers. Although invisible to the naked eye, they are easily seen from great distances when using NVGs. The application of lasers within the cockpit necessitates that laser eye protection (LEP) be worn to protect the eyes from accidental exposure.

LEP filters are manufactured to provide protection by passively attenuating specific, predetermined laser wavelengths by either absorption or reflection (Sheehy, 1988). When worn in combination with NVGs, the protective eyewear is placed between the user's eye and the eyepiece lens of the NVG. Any type of LEP could potentially attenuate the brightness of the intensified image at the user's eye. This could degrade NVG-aided visual acuity, thus compromising the safety of NVG operations.

Fiedler, Riegler, and Demitry (1998) evaluated the effects of absorptive LEP devices on visual acuity with NVGs. In this experiment, F4949C NVG-aided visual acuity (and later F4949G NVG-aided visual acuity), with and without FV-9 LEP technology was assessed under illumination conditions equivalent to 0.25 moon disk and clear starlight, with medium and low contrast targets. NVG-aided visual acuity was assessed using square-wave grating resolution patterns, placed 20 feet from the subject. The NVG resolution chart was illuminated by a Hoffman Night Sky Projector at two illumination levels and verified by using a photometer between trials. Each subject read the resolution patterns from left to right and top to bottom, thus each pattern was viewed eight times. Subjects reported whether the patterns were horizontal or vertical, responses were totaled and visual acuity values were determined using a 75 percent correct standard. The results showed significant decrements in NVG-aided visual acuity due to LEP occurring only at starlight illumination at both contrast levels. Visual acuity under NVG+LEP viewing was degraded relative to baseline NVG visual acuity at all experimental conditions, resulting in an overall reduction of 8.7 percent. Furthermore, the degradation in NVG-aided visual acuity due to LEP was greater at starlight illumination compared to 0.25 moon disk illumination.

At the request of the Air Force Research Laboratory Human Effectiveness Directorate Office, Riegler and Fiedler (1999) assessed the effects of two samples of the WARDOVE LEP spectacle (WD-1 and WD-2) on NVG-aided visual acuity using the F4949C and F4949G NVGs. The main distinction between the two prototypes is the wider range of transmittance for the WD-2. NVG-aided visual acuity was assessed using square-wave grating resolution patterns, placed 20 feet from the subject. The NVG resolution chart was illuminated by a Hoffman Night Sky Projector at two illumination levels and verified by using a photometer between trials. Each subject read the resolution patterns from left to right and top to bottom, thus each pattern was viewed eight times. Subjects reported whether the patterns were horizontal or vertical, responses were totaled and visual acuity values were determined using a 75 percent correct standard. It was found that neither WARDOVE LEP spectacle had a significant effect on NVG-aided visual acuity at the illumination and contrast conditions tested. These findings and those reported by Fiedler et.al., (1998) using absorptive LEP indicated that reflective LEP has less detrimental impact on NVG-aided visual acuity. Improvements in intensifier tube resolution, SNR, and gain contribute to improvements in NVG-aided visual acuity both with and without LEP (Riegler et.al., 1999).

NVGs can be severely affected by external light sources as well. Incompatible lighting sources, such as cockpit displays or aircraft landing lights, can degrade visual acuity by creating a washout or halo effect in the user's image. Most cockpit lighting is produced using incandescent bulbs filtered to produce red, white, or blue lighting for unaided night flying. The filtered incandescent lights, however, emit an enormous amount of near infrared energy to which the NVGs are very sensitive (700 nm to 900 nm) (Task, 1992).

To achieve compatibility and avoid losses in NVG-aided visual acuity, cockpit lighting should have a spectral distribution containing little or no overlap with the spectral response of the NVG. NVG compatible cockpit lighting requirements differ depending on the class of NVG being used. Class A and Class B NVGs differ in the spectral transmission characteristics of their minus-blue objective lens filter. Class A NVGs are filtered so they will not sense and intensify light at wavelengths shorter than 50 percent transmission at 625 nm (orange region of the spectrum) and Class B NVGs are filtered so they will not sense and intensify light at wavelengths shorter than 50 percent transmission at 665 nm (middle of red region of the spectrum).

The spectral energy distribution of NVG-compatible cockpit lighting peaks between 530 and 560 nm, a spectral distribution not compatible with a Class B NVG filter until a modified Class B filter (Class C NVG) was introduced. Characteristics of the Class C NVG were modified with an added bandpass feature to allow limited transmission of energy in the region of 545 nm as illustrated in Figure 4.

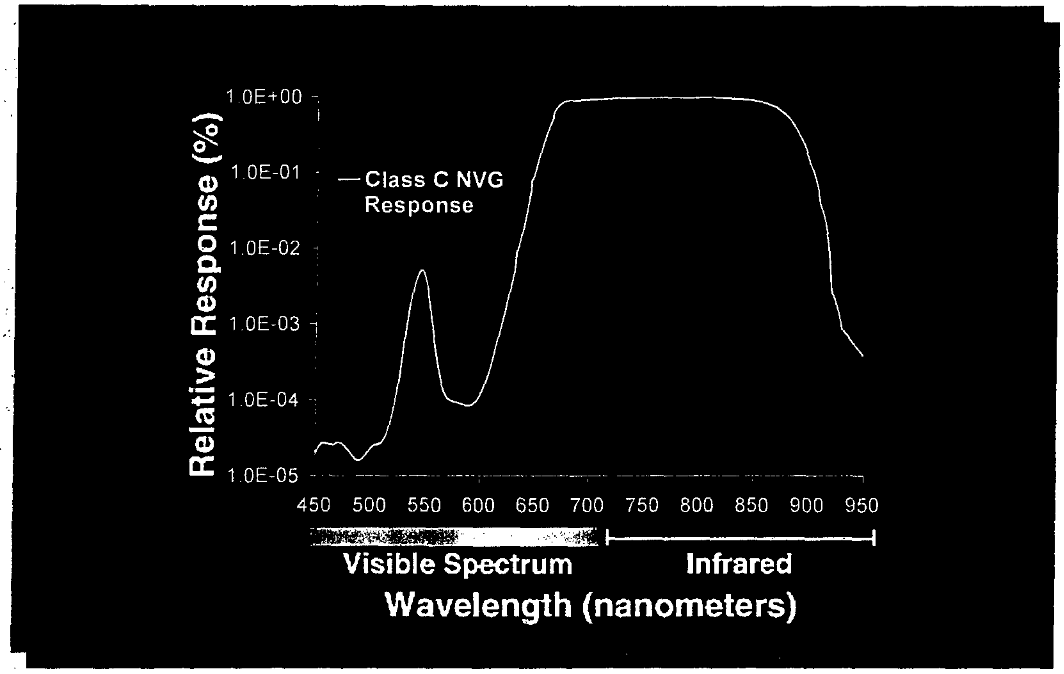

Figure 4. Energy transmission of the "leaky" green filter (Antonio, et.al., 2004).

Gibb and Reising (1997) conducted an experiment testing whether the modified Class B filter is compatible in accordance with specified criteria and to compare the USAF Tri-Bar Chart and NVG Chart to determine whether NVG-aided visual acuity results differed when incompatible light is present. Subjects focused NVGs on the USAF Tri-Bar Chart to obtain maximum resolution. NVG-aided visual acuity was measured using the USAF Tri-Bar and NVG Charts. All charts were placed 20 feet from the objective lens of the NVG. Charts were illuminated and radiance was adjusted to the necessary criterion. A halogen bulb enclosed in a metal housing was used to simulate cockpit lighting such as a warning indicator in most aircraft. Cockpit lighting was then illuminated while the subject viewed the charts to assess whether resolution was degraded. A Night Vision Imaging System (NVIS) Green B filter was placed in front of the simulated cockpit lighting to provide minimal degradation and a NVIS red filter was used to provide a large degradation condition. Each subject read the resolution patterns from left to right and top to bottom under each of the possible orientations. Responses were totaled and visual acuity values were determined using a 75 percent correct standard. Results indicated that NVG-aided visual acuity did not significantly differ between the USAF Tri-Bar Chart and the NVG Chart and the modified Class B NVG is compatible with the current requirements.

The review of NVG visual performance literature revealed invaluable information about NVG technology, NVG operational visual performance limitations, and visual acuity assessment. Technological advances in image intensifier tube design have led to the F4949G-TG Pinnacle™ goggle featuring an auto-gated power supply and thin-filmed technology. The Pinnacle's™ thin-filmed technology gave the image intensifier tube an increase in the signal-to-noise ratio characteristic. It has been well established by Riegler et.al. (1991) that there were improvements in visual performance as an image intensifier tube's signal-to-noise ratio increased. However, there has been no study accomplished in which visual performance is measured and compared with the F4949G-TG goggles. Visual acuity has been widely used as a metric to measure visual performance while assessing differences between NVG technologies. Boff and Lincoln (1988) cite three common methods of visual acuity assessment; Snellen Letter Charts, Square-Wave Grating Charts, and Landolt C Charts. The Landolt C, however, has been proposed as the standard optotype and method of visual acuity assessment. Landolt Cs can be efficiently presented on a computer monitor in one of eight orientations and in an automated and controlled visual acuity measurement using the FrACT software.

Method

Participants

Twelve volunteers participated in the study. All participants were US government employees, military officers, and enlisted personnel. Their ages ranged from 22 to 42 with a median of 33 and an average age of 33. All participants had a least 20/20 unaided or corrected visual acuity and received specific training on F4949 NVG adjustment procedures (Antonio & Berkley, 1993). Participants requiring correction to attain 20/20 visual acuity wore their correction throughout the entire experiment. All participants attained at least a 20/35 NVG-aided visual acuity after NVG adjustments using a high contrast NVG resolution chart illuminated to full moon equivalent. Prior to testing, each subject received an informed consent briefing and signed an Informed Consent Document.

Apparatus

This study was conducted in the night vision human factors laboratory at the Air Force Research Laboratory (AFRL/HEA) in Mesa, AZ. The room measured 37 feet long and 16 feet wide with black carpet and black walls specifically designed for night vision device testing.

The visual acuity stimuli were presented via a workstation Intel® Pentium, Microsoft Windows 2000 equipped computer positioned at the experimenter's table. The computer contained the Freiburg Visual Acuity and Contrast Test software program that presented the visual stimuli simultaneously to the experimenter's monitor and the participant's monitor. The participant's monitor was a 17-inch Silicon Graphics Color Graphic Display CRT monitor. This monitor was connected to the computer using component video cables, allowing for video color to be transmitted in red, green, and blue, or RGB format. Only the component blue video was connected to the monitor, to allow only blue color to be transmitted from the computer to the monitor. Unlike the human eye, third generation NVGs are not as sensitive to light at the blue end of the visual spectrum. The dielectric coating (minus blue filter) incorporated in the objective lens of the NVG severely attenuates energy below 625 nm and is designed to provide compatibility with blue lighting, thus the monitor image did not overdrive the NVG. The participant's monitor was positioned 20 feet from the NVGs at a height of 45 inches to match the height of the goggles. The experimenter's monitor was a 21-inch View Sonic Graphics Display CRT monitor positioned at the experimenter's workstation to the side and slightly behind the participant's table. The participant used a standard computer keyboard with a complete nine-key number pad, sufficient for responding to the visual acuity stimuli.

Two AN/AVS-9 (F4949 series) NVGs were used in this experiment. NVG specifications are displayed in Table 2 (J. Soderberg, personal communication, October 14, 2005). One NVG (F4949G-TG) was equipped with the auto-gated, thin-filmed Pinnacle™ image intensifier tubes. The second NVG (F4949G) was equipped with image intensifier tubes with conventional power supplies and technology.

Table 2

Specifications for F4949G and F4949G-TG Tubes Used in the Study

GOGGLE MODEL	F4949G	F4949G-TG
GOGGLE SERIAL #	4151	10771
MANUFACTURER	ITT	ITT
PHOTOSENSITIVITY (uA/lm)	1800	2400
SPECTRAL RESPONSE	Class B	Class B
RESOLUTION (lp/mm)	64	72
SIGNAL-TO-NOISE RATIO	22:1	29:1
LUMINANCE GAIN @ 2 X 10^{-6} fc (fL/fc)	40000	69000
HALO MAX (mm)	1.25	0.61

A pair of 2-inch by 2-millimeter thick neutral density (ND) filters was placed in a mount in front of each NVG objective lens to attenuate the monitor radiance and produce clear starlight and overcast starlight illumination conditions. A ND filter of 0.5 was required to simulate clear starlight and a ND filter of 1.6 was required to simulate overcast starlight.

Participants were seated in an adjustable office chair at a table positioned 20 feet from the monitor and foam-core background. A NVG mount bracket and an adjustable chin-rest assembly were securely fastened to the table.

Background illumination was provided by a broadband halogen light source positioned off axis at 20 feet from the display. A 4-inch by 4-inch black square was mounted on a tripod 5 feet in front of the broadband halogen lamp. The black square was used to shadow the participant's monitor, shielding it from illumination and avoiding glare on the participant's monitor. The illuminated white foam board subtended approximately 23 degrees horizontal and 12 degrees vertical of the NVG 40-degree field-of-view. The CRT display, viewed through a square aperture centered at the lower portion on a white foam board, subtended approximately 3 degrees horizontal and 2 degrees vertical of the NVG 40-degree field-of-view. See Figure 5 for the experimental configuration in the night vision lab.

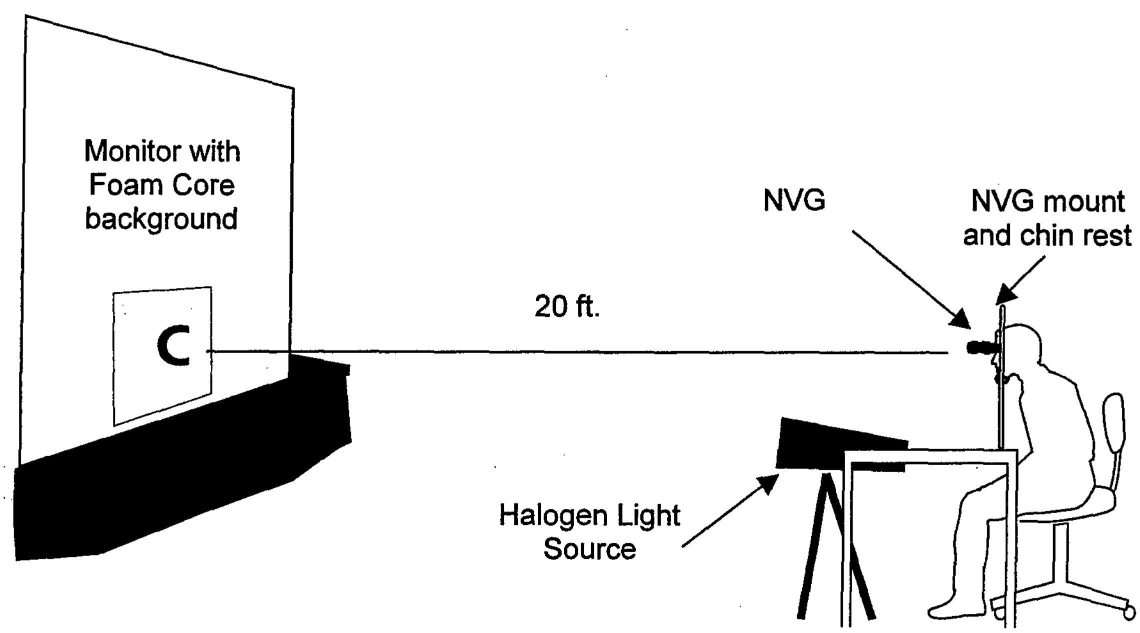

Figure 5. Representation of the experimental configuration in the night vision lab.

A high contrast resolution chart consisting of nine square wave gratings was used for NVG focusing procedures. The chart was illuminated with an infrared LED (851 nm) positioned 20 feet from the background. Focusing and initial NVG-aided visual acuity was assessed using the square-wave grating resolution chart.

Stimuli

The stimuli in this study were Landolt C visual acuity targets of varying sizes and contrasts. The Landolt Cs were presented on the monitor using the "Freiburg Visual Acuity and Contrast Test" automated computer software program (Bach, 1996). The test always started by presenting a letter C at a gap visual angle of 10 minutes of arc (20/200 Snellen). Landolt Cs were presented on a monitor in one of eight orientations and the participant pressed one of eight buttons that corresponded to the eight positions of the Landolt C's gap (eight-alternative forced-choice task), as seen in Figure 6. The size of the C (e.g. gap visual angle) was adjusted based on the participant's responses. Twenty-four presentations were run to estimate the acuity. After each trial the final visual acuity measurement was calculated by the FrACT software to determine the letter size that would have been seen 56.25 percent of the time using the "best PEST" (Parameter Estimation by Sequential Testing) algorithm (Lieberman & Pentland, 1982), based on the viewing distance set to any value and presented in large type on the screen, either in Snellen format or as decimal acuity (Snellen's fraction).

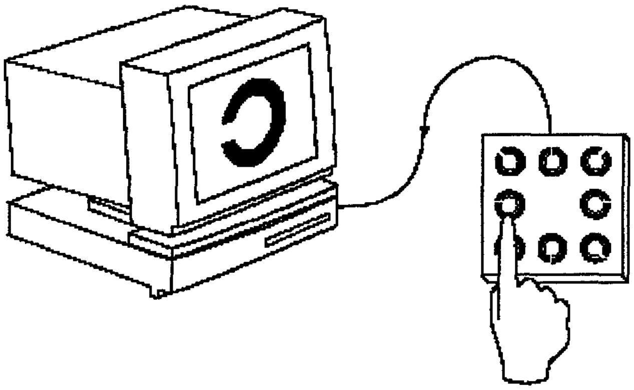

Figure 6. Schematic setup of the "Freiburg Visual Acuity and Contrast Test" (Bach, 1996).

Adjusting the brightness and contrast levels of the CRT monitor and software program allowed for the simulated 0.25 moon disk illumination and contrast levels of 52 and 19 percent. Contrast levels were measured as contrast modulation [Luminance_{max} - Luminance_{min}] / [Luminance_{max} + Luminance_{min}]. The ND filters positioned in front of the goggles, allowed for the simulated clear starlight and overcast starlight illumination conditions while maintaining the two contrast levels. The filters were attached or removed according to the random schedule of viewing conditions. Illumination levels were verified using a Photo-Research PR-1530AR spot radiometer prior to each experimental session. The three illumination levels (0.25 moon disk, clear starlight, and overcast starlight illumination), as seen in Table 3, were defined according to Night Vision Imaging System (NVIS) Radiance levels. NVIS radiance represents the amount of energy within the spectral response range of the NVG that would be reflected from a defoliated tree under a given ambient illumination condition (Riegler et.al., 1999).

Table 3

The NVIS Radiance Values Corresponding to Three Illumination and Two Contrast Conditions Used in the Experiment

MEDIUM CONTRAST (52 percent)		
	Monitor Background	**Monitor Target Stimuli**
0.25 Moon (no ND filter)	5.45×10^{-10} NR_B	1.75×10^{-10} NR_B
Clear Starlight (using 0.5 ND filter)	1.9×10^{-10} NR_B	0.6×10^{-10} NR_B
Overcast Starlight (using 1.6 ND filter)	0.25×10^{-10} NR_B	0.08×10^{-10} NR_B

LOW CONTRAST (19 percent)		
	Monitor Background	**Monitor Target Stimuli**
0.25 Moon (no ND filter)	5.45×10^{-10} NR_B	3.7×10^{-10} NR_B
Clear Starlight (using 0.5 ND filter)	1.8×10^{-10} NR_B	1.2×10^{-10} NR_B
Overcast Starlight (using 1.6 ND filter)	0.26×10^{-10} NR_B	0.18×10^{-10} NR_B

Experimental Design

The experiment employed a 3 x 2 x 2 within-subjects repeated measures factorial design. The independent variables consisted of ILLUMINATION (0.25 moon disk, clear starlight, and overcast starlight), CONTRAST (52 and 19 percent), and NVG MODEL (F4949G and F4949G-TG). The dependent variable consisted of NVG-aided visual acuity reported as logMAR acuity.

Procedure

Each participant completed two sessions, on different days, to collect data from each NVG model separately. Each session lasted approximately 1 to 1.5 hours. Trials were completed across two sessions to eliminate any variability associated with eye fatigue. Unaided visual acuity was recorded for each participant using the OPTEC Air Force Vision Tester 2300, which is commonly used in Air Force optometry clinics to verify each participant has 20/20 vision or better. Once uncorrected or corrected 20/20 vision was verified, each participant was comfortably seated at the table containing the NVGs attached to a table-mounted stand. Prior to data collection, each participant adapted to the darkened test lane for 10-15 minutes. The height and interpupillary distance of the NVGs were adjusted individually for each participant. The NVG objective lens focus was pre-set by the experimenter for the viewing distance of 20 feet. Participants adjusted each NVG diopter eyepiece focus to achieve their best visual acuity on the high contrast resolution chart.

The participant viewed the monitor through the NVGs in each trial. Experimenter 1 confirmed the participant was appropriately positioned behind the NVG, the participant's fingers were positioned appropriately on the keyboard, and the participant was ready. Once the participant was ready to proceed, experimenter 2 removed the "blinder" from the monitor, signaling experimenter 1 to start the trial. The "blinder" was a white foam board large enough to cover the monitor. Experimenter 2 used the "blinder" to block the monitor from the participant's view to ensure the bright light irradiating from the monitor, as the software program displayed visual acuity results between each trial, did not affect the participant.

Once experimenter 1 initiated the trial, a Landolt C stimulus was presented, at one of eight orientations, for 3 seconds. The test always started by presenting a letter C at a gap visual angle of 10 minutes of arc, equivalent to 20/200 in Snellen format. The computer software adjusted the size of the C based on the participant's responses. As the participant made a correct response, indicating the gap in a letter C with the directional arrows on a computer keyboard, the letter size was reduced. Conversely, if the participant made an incorrect response, the size of the C increased. Each participant was instructed to respond quickly and accurately on each presentation, keeping errors to a minimum. If the participant failed to respond to the stimulus, the software would record an incorrect response. Each participant responded within an average of 1.5 to 2 seconds. Participants viewed 24 Landolt C presentations to complete one visual acuity trial. Once one trial was completed, the participant then relaxed while still positioned in the goggles.

The final visual acuity measurement, after 24 presentations, was calculated for a letter size that would have been seen 56.25 percent of the time using the "best PEST" (Parameter Estimation by Sequential Testing) algorithm that calculated the maximum visual acuity score on the basis of all previous answers. After each trial, the software displayed the visual acuity on the monitor and also stored the information in the clipboard to be exported to an Excel© spreadsheet for later analysis. Experimenter 1 would initiate the next trial when the participant was ready to continue and experimenter 2 removed the "blinder" from the monitor.

Participants completed at least five practice trials without the use of the NVG and at least ten practice trials viewing with NVGs. More practice trials were allowed if the participant requested to become more familiar with the task. Each participant then completed the 12 experimental conditions (6 with each NVG) under timed interval visual acuity trials presented via the Freiburg Visual Acuity and Contrast Test software. Each condition consisted of 5 trials at 24 presentations per trial, totaling 120 presentations per condition. Test conditions (e.g. illumination level, contrast, and NVG model) were counterbalanced to avoid order effects. Participants did not have any prior knowledge of the NVG model that was used for each session.

The purpose of this research was to determine if there are any significant visual performance differences in NVG-aided visual acuity when using the new F4949G-TG goggles, equipped with image intensifier tubes utilizing thin-filmed technology, as compared to F4949G goggles with conventional technology, while completing a time-constrained visual acuity task. The hypothesis is that an increase in the signal-to-noise ratio will contribute to an improvement in visual performance (e.g. visual acuity scores) while using the F4949G-TG NVG compared to the F4949G NVG.

Results

LogMAR Visual Acuity as a Function of Illumination, Contrast, and NVG

Snellen visual acuity scores were recorded for each individual at each experimental condition. These values were converted to log minimum angle of resolution (MAR) for subsequent data analyses (MAR = 1 / Snellen fraction). According to Holladay (1997), the logarithmic representation of MAR has been recommended for scaling visual acuity since it provides a more of a standard visual acuity designation regardless of testing distances. The acuity scores for the twelve participants, as well as logMAR mean and standard deviation, are reported for each illumination, contrast, and NVG condition in Tables 4, 5, and 6.

Table 4

LogMAR Visual Acuity Values for Each Participant as a Function of NVG and Contrast at 0.25 Moon Disk Illumination

0.25 Lunar Disk Equivalent Illumination				
	Medium Contrast		Low Contrast	
Participant	F4949G	F4949G-TG	F4949G	F4949G-TG
1	0.347	0.255	0.458	0.482
2	0.329	0.327	0.536	0.414
3	0.465	0.436	0.603	0.643
4	0.340	0.359	0.528	0.435
5	0.425	0.391	0.561	0.529
6	0.394	0.482	0.510	0.520
7	0.289	0.310	0.455	0.498
8	0.306	0.294	0.522	0.419
9	0.332	0.284	0.471	0.466
10	0.433	0.371	0.602	0.520
11	0.238	0.218	0.422	0.391
12	0.359	0.349	0.514	0.517
Mean	**0.355**	**0.340**	**0.515**	**0.486**
Std Dev	**0.065**	**0.075**	**0.057**	**0.068**

Table 5

LogMAR Visual Acuity Values for Each Participant as a Function of NVG and Contrast at Clear Starlight Illumination

Clear Starlight Equivalent Illumination				
	Medium Contrast		Low Contrast	
Participant	F4949G	F4949G-TG	F4949G	F4949G-TG
1	0.409	0.424	0.517	0.526
2	0.400	0.470	0.571	0.489
3	0.530	0.539	0.676	0.708
4	0.433	0.419	0.620	0.590
5	0.536	0.471	0.693	0.654
6	0.511	0.518	0.662	0.672
7	0.379	0.362	0.582	0.516
8	0.478	0.403	0.730	0.551
9	0.462	0.360	0.583	0.521
10	0.551	0.451	0.627	0.588
11	0.411	0.366	0.569	0.549
12	0.529	0.470	0.685	0.626
Mean	**0.469**	**0.437**	**0.626**	**0.582**
Std Dev	**0.061**	**0.059**	**0.064**	**0.069**

Table 6

LogMAR Visual Acuity Values for Each Participant as a Function of NVG and Contrast at Overcast Starlight Illumination

Overcast Starlight Equivalent Illumination				
	Medium Contrast		Low Contrast	
Participant	F4949G	F4949G-TG	F4949G	F4949G-TG
1	0.693	0.649	0.881	0.808
2	0.697	0.692	0.942	0.908
3	0.856	0.808	1.000	0.980
4	0.736	0.685	0.931	0.923
5	0.826	0.793	0.980	0.964
6	0.731	0.766	0.899	0.900
7	0.631	0.627	0.882	0.868
8	0.796	0.693	1.045	0.921
9	0.761	0.705	0.981	0.897
10	0.752	0.670	0.950	0.900

11	0.625	0.652	0.904	0.855
12	0.775	0.692	1.032	0.970
Mean	**0.740**	**0.703**	**0.952**	**0.908**
Std Dev	**0.071**	**0.057**	**0.056**	**0.050**

The percent differences of average LogMAR visual acuity values as a function of all experimental conditions are shown in Table 7. These differences in average LogMAR visual acuity values between the two NVG models ranged from 4.3 percent at 0.25 moon disk/medium contrast to 7.0 percent at the clear starlight/low contrast. Table 8 illustrates the Snellen denominator equivalents for the average recorded logMAR visual acuity values.

Table 7

Percent Differences of Average LogMAR Visual Acuity Values as a Function of NVG, Contrast, and Illumination

LogMAR Differences Between F4949G and F4949G-TG Models		
Illumination	Contrast	Percent Differences
0.25 Moon	Medium	4.3
0.25 Moon	Low	5.6
Clear Starlight	Medium	6.7
Clear Starlight	Low	7.0
Overcast Starlight	Medium	5.0
Overcast Starlight	Low	4.7

Table 8

Average Snellen Denominator Visual Acuity Values as a Function of NVG, Contrast, and Illumination

Snellen Denominator Equivalents for Average LogMAR Scores			
Illumination	Contrast	F4949G	F4949G-TG
0.25 Moon	Medium	45.3	43.7
0.25 Moon	Low	65.5	61.3
Clear Starlight	Medium	58.9	54.8
Clear Starlight	Low	84.6	76.5

Overcast Starlight	Medium	109.9	100.8
Overcast Starlight	Low	179.2	161.7

Repeated Measures Within-Subjects Analysis of Variance

A three-way (3 x 2 x 2) repeated measures within-subjects analysis of variance (ANOVA) was conducted on the NVG-aided logMAR visual acuity data using SPSS for Windows Release 12.0. The results of the ANOVA revealed a significant main effect of ILLUMINATION ($F[2,22] = 811.740$, $p < 0.001$), CONTRAST ($F[1,11] = 622.423$, $p < 0.001$), and NVG ($F[1,11] = 12.586$, $p = 0.005$). The ANOVA also revealed a significant interaction involving ILLUMINATION and CONTRAST ($F[2,22] = 14.790$, $p < 0.001$). No other interactions reached the $p < 0.05$ level of significance. The ANOVA results summary is provided in Table 9. The significant main effect of NVG indicated that visual acuity scores significantly differed between the two NVG models. Furthermore, the lack of a significant interaction of either illumination or contrast with NVG indicated that this difference between the NVG models was consistent across all conditions tested. The mean visual acuity scores as a function of illumination, contrast, and NVG model are graphically represented in Figure 7. As evident from inspection of Figure 7, the logMAR visual acuity scores obtained with the F4949G-TG model were lower than those obtained with the F4949G (e.g. superior visual acuity) at all illumination and contrast conditions examined. The significant interaction between illumination and contrast indicated the detrimental effect of contrast on visual acuity was greater at the lower illumination conditions.

Table 9

NVG-Aided Visual Acuity ANOVA Results Summary

Source	df	Sum of Squares	F-value	p
ILLUMINATION	2	4.167	811.740	< 0.001
ILLUMINATIONxSUBJECT	22	0.056		
CONTRAST	1	1.053	622.423	< 0.001
CONTRASTxSUBJECT	11	0.019		
NVG	1	0.040	12.586	= 0.005
NVGxSUBJECT	11	0.035		
LIGHTxCONTRAST	2	0.026	14.790	< 0.001
LIGHTxCONTRASTxSUBJECT	22	0.019		
LIGHTxNVG	2	0.002	1.770	= 0.194
LIGHTxNVGxSUBJECT	22	0.015		
CONTRASTxNVG	1	0.001	0.816	= 0.386
CONTRASTxNVGxSUBJECT	11	0.015		
ILLUMINATIONxCONTRASTxNVG	2	0.000	0.052	= 0.949
ILLUIMINATIONxCONTRASTxNVGx SUBJECT	22	0.014		

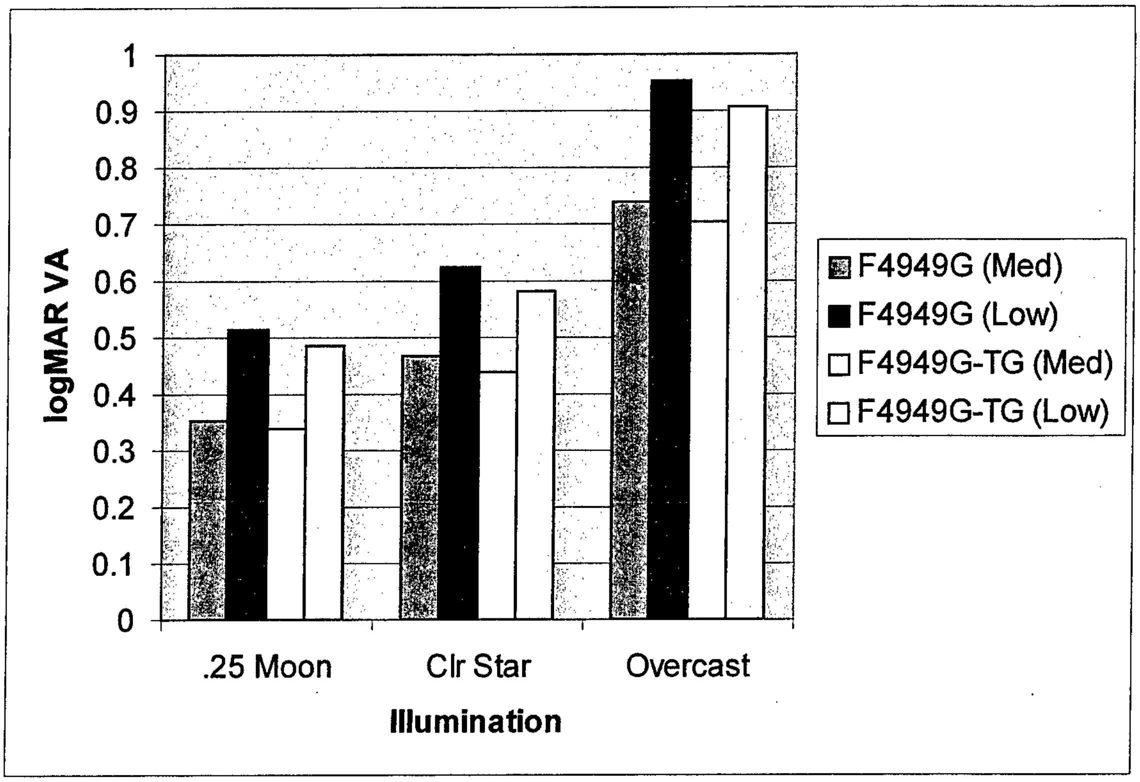

Figure 7. LogMAR visual acuity values as a function of illumination, contrast, and NVG model.

Discussion

Purpose of Present Study

The primary purpose of this study was to examine the relationship between NVG image intensifier tube signal-to-noise ratio differences and NVG-aided human visual acuity. Two NVG models equipped with image intensifier tubes of different signal-to-noise ratios were examined in this study. The F4949G-TG image intensifier tubes with thin-filmed technology had a higher signal-to noise ratio of 29:1, while the F4949G image intensifier tubes had a signal-to-noise ratio of 22:1. The two models vary with respect to signal-to-noise ratios, as well as other specifications that impact the overall quality of the NVG image. The signal-to-noise ratio takes into account the photosensitivity of the tube and the "noise" contribution of the microchannel plate. Photosensitivity is the ability of the tube to detect light energy and convert it to an electron image. As the photosensitivity of the tube increases, the user has a better ability to see under darker conditions. The photosensitivity was 1800 uA/lm and 2400 uA/lm respectively for the F4949G and F4949G-TG.

Improvements in the photocathode and MCP results in increased gain and resolution. The higher the gain of an image intensifier tube for a given ambient lighting level gives a higher output luminance, which should result in greater visual performance (Task, 1992). A typical value for F4949G tubes is 40,000 fL/fc when referring to brightness gain, whereas the F4949G-TG tubes had a brightness gain of 69,000 fL/fc. The F4949G-TG tubes have a higher resolution, which could give the user the ability to view a clearer and sharper picture. The resolution measured in the center (e.g. viewer's focal view) of the NVG image for the F4949G tubes was 64 lp/mm while the central resolution for the F4949G-TG tubes was 72 lp/mm. Since the signal-to-noise ratio takes into account photosensitivity, gain, and resolution, it is the best single indicator of image intensifier performance (Turpin, 2001). No published studies have been identified that directly examines the effect of signal-to-noise ratio on NVG-aided visual acuity since 1991.

NVG-Aided Visual Acuity Results

The results of the present study demonstrated that the F4949G-TG model allowed for superior visual acuity scores in all conditions. Therefore our hypothesis was supported by the data. An increase in signal-to-noise ratio did contribute to the difference in visual performance (e.g. visual acuity scores) between the F4949G and F4949G-TG NVG models.

Although statistically significant, NVG-aided visual acuity differences between the two NVG models were small (averaging about 0.025 log units). This difference represents approximately two characters on a visual acuity chart. While using a typical Bailey-Lovie acuity chart, there are 10 steps between the 0.0 and 1.0 logMAR levels and proceed in 0.1 log unit steps (Bailey, 1980). Each log unit step has five characters in a line, accounting for 0.02 log units. The NVG-aided visual acuity differences range from 0.015 log units at the 0.25 moon disk illumination and medium contrast condition to 0.044 log units at the overcast starlight and low contrast condition. Therefore, the largest difference in visual acuity between the two NVGs was about half a line on a standard visual acuity chart. The operational relevance of these differences in NVG-aided visual acuity in a NVG flight environment is probably marginal across the range of illumination and contrast levels examined in this study.

The significant effect of illumination and contrast on NVG acuity was as expected and consistent with previous research. Improved visual acuity was recorded at higher illumination and contrast levels and decreasing visual acuity was recorded at lower illumination and contrast levels. The detrimental effect of contrast on decreasing visual acuity was greater at lower illuminations. (Fiedler et.al., 1998; Levine and Rash, 1989; Riegler et.al., 1991; Kotulak and Rash, 1992).

Comparison to Previous Signal-to-Noise Ratio/Visual Acuity Study

A previous study that examined the signal-to-noise ratios on NVG-aided visual acuity tested image intensifier tubes with signal-to-noise ratios ranging from 11.5 to 18 (Riegler et.al., 1991). These researchers found larger improvements in visual acuity due to signal-to-noise ratio increases than those observed in the present study. Furthermore, Riegler et.al. found that the effect of an increase in signal-to-noise ratio on NVG-aided visual acuity significantly increased with a decrease in illumination.

The most plausible explanation for the difference of the effect of signal-to-noise ratio on NVG-aided visual acuity in the present study compared to the Riegler et.al., 1991 study is that there appears to be an asymptotic relationship between increases in signal-to-noise ratio and NVG-aided visual acuity. Riegler et.al. also described this non-linear relationship between signal-to-noise ratios and NVG-aided visual acuity and found this relationship to exist at all conditions of their investigation. For example, these researchers reported that an increase in signal-to-noise ratio from 12 to 18 resulted in a 22 percent increase in NVG-aided visual acuity at clear starlight and 20 percent contrast. However, the majority of the visual acuity increase was observed in the first 3-unit increase of signal-to-noise ratio, from 12 to 14, which resulted in a 15 percent increase in NVG-aided visual acuity. Further increases from 15 to 18 at the same condition only increased NVG-aided visual acuity by an additional 7 percent. Riegler et.al. suggested that the signal-to-noise ratio to NVG-aided visual acuity relationship begins to asymptote at a signal-to-noise ratio of approximately 20. The current study provides empirical data to support this assertion by demonstrating a significant but small, 7.0 percent, increase in NVG-aided visual acuity as a function of signal-to-noise ratio at the clear starlight and 19 percent contrast condition for NVGs with signal-to-noise ratios of 22 and 29. In summary, the present findings confirm that increases in NVG image intensifier tube signal-to-noise ratios will have their greatest benefit to visual acuity between the signal-to-noise ratio ranges of 10 to 20. Further increases in signal-to-noise ratios (from 20 to 29) may result in noticeable enhancements in NVG image quality, but these differences are likely to have little impact on visual acuity levels across the range of conditions examined in these studies. The present study also provides data to describe the function between signal-to-noise ratio and NVG-aided visual acuity at overcast starlight illumination, a condition not examined by Riegler et.al., 1991.

Visual Acuity Results Using FrACT Versus Chart Presentation

This present study extended the use of the FrACT visual acuity task to examine NVG-aided visual acuity at a wide range of illumination and contrast conditions. Angel and Baldwin (2003) conducted the only known visual acuity experiment using NVGs and the FrACT presentation. Their study, using F4949G model NVGs, revealed NVG-aided visual acuity ranging from about 20/25 to 20/50, at 0.25 moon disk illumination (1.58 X 10^{-9} watts/cm^2) and 50 percent contrast. Therefore, use of the FrACT software enabled us to obtain results comparable to previous research, noticeably at the 0.25 moon disk illumination and 50 percent contrast conditions.

Loss of visual performance can depend on the size and contrast of the elements of the task, whether viewing time is limited, and whether fatigue becomes a factor (Richards, 1977). In this study, NVG-aided visual acuity using FrACT was slightly worse than NVG-aided visual acuity assessed using grating charts or Landolt C charts (Riegler and Fiedler, 1999; Riegler et.al., 1991; Pinkus and Task, 1999; Gibb and Reising, 1997). All NVG-aided visual acuity procedures will result in different absolute levels of acuity depending on the target (Landolt C, grids, letters, etc.), how illumination is characterized (radiance on chart, brightness in NVG image, etc.), method of presentation (chart versus monitor), duration of presentation, and single or multiple character presentation. All these factors will influence the visual acuity score.

For example, Riegler and Fiedler's 1999 LEP study showed visual acuity with F4949G model NVGs was about 20/35, compared to about 20/45 in the present study, at 0.25 moon disk illumination and medium contrast. These researchers used grating charts that allowed for only a two-alternative forced-choice test versus the eight-alternative forced-choice test allowed with the FrACT software. Also viewing time was not limited to 3 seconds, so observers could have used eye movements to improve visual acuity scores while reading across a line. Limiting viewing time to 3 seconds and using single character presentation, in the present study, may have contributed to poorer visual acuity scores, but it was well understood that limiting the time each stimulus was presented could cause a loss of visual performance.

A comparison of presentation methods (e.g. monitor versus chart) made between a 1989 and 1991 study show similar NVG-aided visual acuity differences, as a function of the method used, to the most current studies to include the present study. The comparison demonstrated a NVG chart presentation yielded better visual acuity results in the studies reviewed. Levine and Rash's 1989 study, although with AN/PVS-5A NVGs, used a computer monitor single character presentation of the letter E. They yielded visual acuity scores of 20/50 in twilight and high contrast conditions and as low as 20/200 at the lowest luminance and contrast level. Riegler et.al. (1991), using AN/PVS-7 NVGs, studied the effect of SNR on NVG-aided visual acuity by using a Landolt C chart under two illumination and contrast conditions. They yielded visual acuity scores of 20/42 in the highest illumination conditions to as low as 20/175 in the most degraded visibility conditions. The comparison of these studies demonstrate a trend, similar to comparisons with the present study, that visual acuity scores can tend to be better with studies using chart presentation versus a monitor presentation

FrACT Advantages and Disadvantages

Using a computer controlled task like the FrACT is advantageous because it uses a Landolt C stimuli presentation, it controls duration of stimulus, allows for 8 orientations (giving an eight-alternative forced-choice test), and it calculates an average visual acuity score recorded for all the presentations in a complete trial. With proper NVG filtering and monitor adjustment, light levels can be controlled and the monitor contrast can remain stable. In summary, using the FrACT software adds a level of control that is more difficult to achieve with charts. Small differences in NVG-aided visual acuity, like those obtained in this study, may not have been as noticeable without using a computer controlled task. The disadvantages of using the FrACT software to assess NVG-aided visual acuity are the lack of brightness control of the monitor when the visual acuity results are presented between each trial and the lack of direct control, through the software settings, for brightness and contrast levels of the background and target.

Recommendations from Present Study

A better alternative to the current version of the FrACT software might be a computer controlled Landolt C task that is tailored to NVG applications. An automated procedure for self-administered measurement of visual acuity that could be tailored to NVG applications would allow the experimenter to select exact illumination and contrast conditions. These illumination and contrast levels would be consistent with published specifications and could be pre-programmed into the software. Additional accessories such as neutral density filters could also be included.

The conclusions from this first-ever visual performance comparison between the F4949G-TG and F4949G goggles should be incorporated into the military night vision goggle training curriculum. Night vision goggle instructors and students would greatly benefit from knowing the most current data available with the newest night vision goggle technology. Night vision device designers and acquisitionists should consider this new visual acuity data from this F4949G-TG and F4949G goggle comparison when considering the best match of night vision technology and operational requirements. Departmental monetary funds are rarely spent without close scrutiny, so it would be of great benefit to know how this new image intensifier tube technology will be best utilized.

Military senior leadership should consider the types of night vision technology needed to support specific operational requirements. This NVG-aided visual acuity data showed that the increase in the signal-to-noise ratio (from 22 to 29) demonstrated a statistically significant but small increase in NVG-aided visual acuity, especially as illumination conditions became darker. Conditions such as the clandestine darkness of a desert or jungle environment would be ideal conditions for the F4949G-TG NVGs to be utilized. More importantly and believed to be of greater operational impact, military commanders should utilize the F4949G-TG technology in conditions in which the image intensifier tubes are designed to give the user the greatest advantage over the enemy. The F4949G-TG image intensifier tubes have been designed to enable the user to operate in culturally lit nighttime conditions. These specific design improvements may correlate into an enhanced image quality and increased visual performance in urban environments.

Recommendations for Future Research

Future research should address the impact of image intensifier tube differences on a wider range of visual performance tasks. For instance, the effect of signal-to-noise ratio on contrast sensitivity and on a NVG visual search task would add important and relevant information regarding the impact of new NVG technologies on NVG operational performance. Visual performance metrics such as contrast sensitivity and NVG visual search patterns combined with the corresponding visual acuity measured could provide a more comprehensive index of visual performance than just visual acuity alone. Contrast sensitivity tests measure the contrast threshold for a particular spatial frequency and allow the researcher to choose the spatial frequency (different stimulus sizes) to measure (Gibb and Reising, 1997). Visual search is the systematic visual coverage of a given area so that all parts of the area are observed. The purpose of a visual search is to detect objects or activities on the ground. The use of the NVG greatly enhances the night visual search capability, but some loss of search detail can be expected because of the operating limitations of the equipment.

Future research should examine the impact of thin-filmed technology on visual performance in other nighttime conditions such as cultural lighting and urban environments. As previously discussed, the F4949G and F4949G-TG models differ in specifications other than signal-to-noise ratios. The F4949G-TG NVGs have been designed to enable the user to operate in highly lit nighttime conditions. An auto-gating (pulsing) power supply, versus the conventional DC power supply, prevents the photoresponse and gain from being driven down by incompatible urban lighting and the new thin-filmed design effectively reduces the halo and blooming effect. The auto-gated power supply and spacing between the photocathode and MCP of the F4949G-TG goggles helps reduce the size of the halo effects from 1.25 mm in diameter at the output of the image intensifier tube (F4949G NVG used in this study) to 0.61 mm in diameter at the output of the image intensifier tube (F4949G-TG NVG used in this study). These specific design improvements may correlate into an enhanced image quality and increased visual performance in highly lit urban environments with the F4949G-TG NVG. An investigation of the impact of these two NVG technologies on visual performance in an urban nighttime environment is essential.

Conclusion

The purpose of this study was to examine the relationship between NVG I^2 tube signal-to noise ratio differences and NVG-aided human visual acuity. The results of the present study demonstrated that the F4949G-TG model, with a higher signal-to-noise ratio, resulted in superior visual acuity scores in all conditions. Although statistically significant, NVG-aided visual acuity differences between the two NVG models were small.

Previous research found larger improvements in visual acuity due to increases in signal-to-noise ratios than those found in the present study. The most plausible explanation for the difference, suggested by Riegler et.al., 1991, is an asymptotic relationship existing between increases in signal-to-noise ratio and visual acuity.

Visual acuity assessed by FrACT was slightly inferior than visual acuity assessed using charts, however, using a computer controlled task like FrACT is advantageous and adds a level of control that is more difficult to achieve with charts. The disadvantages associated with the FrACT software should inspire a computer controlled Landolt C task that is tailored to NVG applications.

Military senior leadership should consider the types of night vision technology needed to support specific operational requirements. Based on results from this present study, conditions such as in the clandestine darkness of a desert or jungle environment would be ideal conditions for the F4949G-TG NVGs to be utilized. More importantly, military commanders should utilize the F4949G-TG technology in urban conditions in which the image intensifier tubes are designed to give the user the greatest advantage over the enemy.

The impact of I^2 tube differences on a wider range of visual performance tasks, such as the effect of signal-to-noise ratio on contrast sensitivity and a NVG visual search task should be examined. Also future research should examine the thin-filmed technology impact on visual performance in other nighttime conditions such as cultural lighting and urban environments. It is imperative that future research adds important and relevant information regarding the impact of new NVG technologies on NVG operational performance.

References

Angel, S. P., & Baldwin, J. B. (2003). *Aircrew visual acuity viewing with different night vision goggle eyepiece diopter settings*. United States Air Force Research Laboratory: Battlespace Visualization Branch.

Antonio, J.C. & Berkley, W.E. (1993). *Night vision goggle model F4949 preflight adjustment/assessment procedures.* (AL/HR-TR-1993-0111, AD A271 079). Mesa, AZ: Armstrong Laboratory, Aircrew Training Research Division.

Antonio, J.C., Berley, W.E., Fiedler, G., & Joralmon, D.Q. (2004). *Night vision goggle training course, version 3* (1 ed). Mesa, AZ: United States Air Force Research Laboratory.

Bach, M. (1996). The "Freiburg Visual Acuity Test" - Automatic measurement of visual acuity. *Optometry and Vision Science, 73*, 49-53.

Bailey, I. L. (1980). Designation of visual acuity in logarithmic units. *Optometric Monthly, 71*, 80-85.

Bailey, I. L., & Lovie, J. E. (1976). New design principles for visual acuity letter charts. *American Journal of Optometry & Physiological Optics, 53*(11), 740-745.

Boff, K. R., & Lincoln, J. E. (1988). *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH.

Fiedler, G. M., Riegler, J. T., & Demitry, P. F. (1999). *FV-9 laser eye protection: Effects on night vision goggle-aided visual acuity under various illumination and contrast conditions* (Technical Report No. AFRL-HE-AZ-TR-1998-0096). United States Air Force Research Laboratory: Warfighter Training Research Division.

Gibb, R. W., & Reising, J. D. (1997). *Effect of incompatible light on modified class B night vision goggle-aided visual acuity and contrast sensitivity* (Technical Report No. AL/HR-TR-1996-0149). Armstrong Laboratory: Aircrew Training Research Division.

Helmreich, R. L. (2000). On error management: Lessons from aviation. *BMJ, 320,* 781-785.

Holladay, J. T. (1997). Proper method for calculating average visual acuity. *Journal of Refractive Surgery, 13,* 388-391.

ITT Industries, Night Vision. (2005a). *How ITT's development of the Pinnacle thin-filmed image intensifier tube redefined the U.S. military's "view" of night vision technology.* Retrieved December 21, 2005, from http://www.ittnv.com/military/cs_gen3pinnacle.html

ITT Industries, Night Vision. (2005b). *Image Intensifier, Generation 3 18-mm MX-10160 (F9800 Series) - U.S. Customers Only.* Retrieved February 16, 2005, from http://www.nightvision.com/products/files/2006223117580.mx10160_f9800_domestic.pdf

Johnson, C. W. (2004a). The role of night vision equipment in military incidents and accidents. *Human Error, Safety and Systems Development,* 1-16.

Johnson, C. W. (2004b). The operational strengths and weaknesses of military night vision equipment. *Defence Management Journal – Yearbook 2004,* 72-75.

Koenig, R. L. (1997). FAA indentifies CRM-related issues and training needs in flight-inspection missions. *Flight Safety Foundation Human Factors & Aviation Medicine, 44*(1), 1-8.

Kotulak, J. C., & Rash, C. E. (1992). *Visual acuity with second and third generation night vision goggles obtained from a new method of night sky simulation across a wide range of target contrast* (Technical Report No. USAARL 92-9). U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama: Sensory Research Division.

Levine, R. R., & Rash, C. E. (1989). *Visual acuity with AN/PVS-5A night vision goggles and simulated flashblindness protective lenses under varying levels of brightness and contrast* (Technical Report No. USAARL 89-16). U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama: Sensory Research Divsion.

Lieberman, H. R., & Pentland, A. P. (1982). Microcomputer-based estimation of psychophysical thresholds: The best PEST. *Behavior Research Methods & Instrumentation, 14*(1), 21-25.

McLean, W. E., Rash, C. E., McEntire, J., Braithwaite, M. G., & Mora, J. C. (1998). *A performance history of AN/PVS5 and ANVIS image intensifier systems in U.S. army aviation* (Technical Report No. USAARL 98-28). U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama: Aircrew Health and Performance Division.

Miller, R. E., & Tredici, T. J. (1992). *Night vision manual for the flight surgeon* (Technical Report No. AL-SR-1992-0002). Armstrong Laboratory: Ophthalmology Branch.

Mirzu, M. (2000). The design for an objective for night vision applications, taking in account the signal-to-noise ratio criteria. *Photonics, Devices, and Systems, 4016*, 211-216.

Pinkus, A., & Task, H. L. (1998). *Measuring observers' visual acuity through night vision goggles* (Technical Report No. ASC98-1884). United States Research Laboratory: Human Effectiveness Directorate.

Pinkus, A., & Task, H. L. (1999). *Reproducibility of night vision goggle visual acuity measurements using Landolt C's* (Technical Report No. ASC99-2057). Air Force Research Laboratory: Human Effectiveness Directorate.

Plainis, S., Chauhan, K., Murray, I. J., & Charman, W. N. (1999). Retinal adaptation under night-time driving conditions. In A. G. Gale, I. D. Brown, C. M. Haslegrave & S. P. Taylor (Eds.), *Vision in vehicles VII* (pp. 61-70). Amsterdam: Elsevier Science B.V., North-Holland.

Raasch, T. W., Bailey, I. L., & Bullimore, M. A. (1998). Repeatability of visual acuity measurement. *Optometry and Vision Science, 75*(5), 342-348.

Richards, O. W. (1977). Effects of luminance and contrast on visual acuity, ages 16 to 90 years. *American Journal of Optometry & Physiological Optics, 54*(3), 178-184.

Riegler, J. T., & Fielder, G. M. (1999). *Wardove reflective laser eye protection: Effects on night vision goggle-aided visual acuity* (Technical Report No. AFRL-HE-AZ-

TR-1999-0199). United States Air Force Research Laboratory: Warfighter Training Research Division.

Riegler, J. T., Whiteley, J. D., Task, H. L., & Schueren, J. (1991). *The effect of signal-to-noise ratio on visual acuity through night vision goggles* (Technical Report No. AL-TR-1991-0011). Armstrong Laboratory: Human Engineering Division.

Sheedy, J. E., Bailey, I. L., & Raasch, T. W. (1984). Visual acuity and chart luminance. *American Journal of Optometry & Physiological Optics, 61*(9), 595-600.

Sheehy, J. B. (1988). *Laser eye protection: Optical density and transmittance* (Technical Report No. NADC-88028-60). Washington DC: Department of Navy, Naval Air Systems Command.

Sturr, J. F., & Taub, H. A. (1990). Performance of young and older drivers on a static acuity test under photopic and mesopic luminance conditions. *Human Factors, 32*(1), 1-8.

Task, H. L. (1992). *Cockpit/NVG visual integration issues* (Technical Report No. ASC 91-2960). Neuilly Sur Seine, France: NATO Advisory Group for Aerospace Research & Development. (NTIS No. AGARD-LS-187)

Turpin, T. (2001). *Night vision goggles (NVGs) and NVG equipment with market potential.* Retrieved June 18, 2005, from http://www.hf.faa.gov/docs/508/docs/vfNVG_equipment.pdf